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HIGH-TEMPERATURE SUPERCONDUCTORS
FOR SPACE POWER TRANSMISSION LINES

by

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Abstract

Analysis of high-temperature superconductors (HTS) for space power transmission lines shows that they have the potential to provide low-weight alternatives to conventional power distribution systems, especially for line lengths greater than 100 m. The use of directional radiators, combined with the natural vacuum of space, offers the possibility of reducing or eliminating the heat flux from the environment that dominates loss in terrestrial systems. This leads to scaling laws that favor flat conductor geometries. From a total launch weight viewpoint, HTS transmission lines appear superior, even with presently attainable values of current density.

1. INTRODUCTION

The discovery (Wu et al, 1987) of materials that exhibit superconductivity at temperatures above the boiling point of nitrogen has resulted in many efforts to develop these materials into practical conductors for a number of applications. One potential application area for these high-temperature superconductors (HTS) is for low-loss space power systems. Space electrical power systems are particularly appropriate for early power applications of HTS. In such systems, weight/performance is a dominant figure of merit. It is expensive to launch mass. Therefore, conductor systems which, because of their high cost/performance may not be attractive for terrestrial use, may be conductors of choice for space. Aron and Myers (1988) concluded that the primary gain from HTS in large space power systems will be in use as low-loss transmission lines.

Space power systems are highly mission specific. The future trend toward larger power requirements in some missions has prompted the proposal to use nuclear reactors separated from the satellites by high-power transmission lines of tens of meters up to several km length. Hoffman et al (1988) and Oberly et al (1989) showed that a long, dc HTS transmission line connecting a power reactor would be viable even with modest current densities, and that HTS use also seemed justified in lower power systems as well.

This paper explores some of the design considerations for the use of HTS in space power transmission lines.

2. DIFFERENCES BETWEEN TERRESTRIAL AND SPACE DESIGNS

During the past two decades, considerable effort has been expended in the design and testing of prototype low-temperature (< 10 K) superconducting power transmission lines for terrestrial systems. Some of the experience gained is applicable to space power systems. However, there are major differences between terrestrial and space power systems, and these differences must be appreciated to benefit from lessons learned during the terrestrial experience. For a terrestrial system, it is a common misconception that the principle reason for developing superconducting cables is that in general they are much more efficient than alternative power transmission systems. In fact, capital cost reductions ($/MVA-km), power density considerations, and other factors are usually more important motivations. Losses in many terrestrial transmission systems could be reduced, but at higher overall cost. Usually the terrestrial superconducting lines are economic only at sizes of 1000 MVA and higher, and only when underground cables are mandated by right-of-way, environmental, or other social considerations. Analysis of designs for terrestrial transmission lines using HTS is still rudimentary, however, the MVA rating at which such a line would be economic may be considerably lower than that for the low-temperature superconductors (Andeen and Provost, 1989).

In terrestrial transmission systems an important design option to increase the power density is to increase the voltage and current density. The effects of voltage and current density on the weight of the "bare" (i.e., without insulation, mechanical support, etc.) transmission line are shown in Fig. 1. In a space environment, increasing the voltage is more problematic, because of possible arcing problems on exposed components due to the presence of space plasma. In addition, the presence of atomic oxygen degrades the performance of solid dielectrics used in such systems. A rating of 28 V is typical of present space systems, whereas terrestrial systems may be as high as hundreds of kV. Contemporary research in space power systems is devoted to increasing the voltage into the kV range, e.g., by the use of pressurized SF_6 gas enclosures. Because meteoroid penetration of enclosures is always a possibility, the trend toward higher voltages presents many technical challenges. An alternating direction is to increase the current density. For normal conductors, current density is limited by the ability to adequately cool the conductor. Low-loss systems, such as those provided by superconductors, are required in this option to prevent power transmission losses from becoming prohibitive.

A transmission line is a long-length, small cross-sectional area device with a relatively large surface area to volume. Because the ambient temperature in a terrestrial system is about 300 K, system losses for cryogenic transmission lines are dominated by heat leaking into the line. This heat must be removed by a refrigeration system at a substantial refrigeration factor penalty (watts of electricity to run the refrigerator per watt of cooling at the load temperature). In this case, a superconducting system is favored more and more over a conventional underground system as the power transmission level becomes greater. This is because the amount of power that can be transmitted scales roughly with the size of the cables, i.e., with the cross-sectional area of the enclosure, while the heat inleak per unit length scales only in proportion to the perimeter of the enclosure.

Thus the power handling capability scales as the square of the diameter of the enclosure while the heat inleak scales as the diameter.

In a terrestrial design, the terminal ends are fixed so that no axial contraction can be tolerated upon cooldown. This requirement constrains the design of the cable. In space, it may be possible to relax this constraint.

3. GENERAL DESIGN CONSIDERATIONS

The total weight of a power transmission system includes the weight of all transmission lines, conversion equipment, and the refrigeration system and excess power supply that is required to overcome losses and power the refrigerator. There must also be cable termination devices that are required to make the transition from the cryogenic temperature of the cable to the ambient temperature of the load or source. Power conversion equipment generally tends toward less weight with higher frequencies. This must be traded off against the ac losses, which increase as frequency increases. The cable must be designed for abnormal conditions such as conductor quench, operation with the refrigeration system shut down, and operation with electrical overloads.

3.1. DC VS AC

The total loss in any power transmission system can generally be separated into two components: a terminal loss which is independent of circuit length, and a line loss which is proportional to length. Terminal losses for ac systems include the losses in transformers and other substation equipment. In a dc system the losses in the ac–dc conversion (and dc–ac inversion) devices and peripheral equipment (e.g., transformers, filtering capacitors, reactors, etc.) must also be included.

Dc transmission lines have little or no intrinsic conductor loss, however, they require heavy and lossy inverters to couple to power systems at each end of the line, and they are thus at a disadvantage for short lengths. Ac transmission lines incur loss, but it is relatively easy to couple to other ac power systems via transformers.

3.2. CABLE DESIGN

Terrestrial superconducting cable designs have been of a coaxial configuration with full current capability in both inner and outer conductors. They have been shown theoretically to be more economic than other geometries (Guthrie 1971). The magnetic and electric fields in this design are confined to the annular space between the inner and outer conductors.

Design of terrestrial superconducting cables have generally included flexibility (Forsyth et al, 1973, Sutton and Ward, 1977). Advantages gained with the use of flexible cables include: (1) the cable can be reeled prior to deployment, and (2) thermal contraction upon cooldown or heatup does not unduly stress the superconductors. Compared with rigid tube designs this construction has the advantages of longer fabrication length, higher dielectric strength, and accommodation of axial contraction.

To make flexible cables, the conductors are fabricated from helically wound tapes. This configuration allows thermal contraction differences between the conductors and the insulation between the coaxial lines. The lay angles of the conductor strips are chosen to meet the requirements of thermal contraction and magnetic pressure from large fault currents. The dielectric is a flexible annulus of lapped polymer tape impregnated with coolant (supercritical helium) and bounded by electrostatic screens which prevent electric stress concentrations at the edges of the conductor strips. An armour layer is usually required to give the cable mechanical integrity.

A single helix gives rise to added loss due to a net axial magnetic flux, which produces eddy currents in the containment structure of the cable. In addition, the axial flux gives rise to a longitudinal voltage drop on the outer conductor of the cable. A design that has been adopted by Brookhaven National Laboratory (BNL) uses a double helix for each conductor, each helix wound in the opposite sense (Morgan and Forsyth, 1976). This configuration gives rise to some additional loss mechanisms, which are not yet completely understood (Forsyth, 1988).

3.3. LOSSES

In determining losses, one must distinguish between losses at ambient temperature, which contribute simply to reducing efficiency, and losses at cryogenic temperature, which must be multiplied by the appropriate refrigeration factor to translate into total refrigeration power loss. At 7 K in the BNL system, 400W/W was the refrigeration factor.

The major losses in a superconducting power transmission system, include: (1) current-dependent losses in the superconductor, (2) voltage-dependent losses in the insulation, (3) heat leakage of the cryogenic enclosure containing the cables, and (4) losses associated with pumping the cryogenic refrigerant. The first three losses form the load for the refrigeration system. Heat leakage into the enclosure and voltage-dependent losses must be absorbed regardless of the power carried by the cables. Of the four losses, the current-dependent loss in the superconductor is the most difficult to calculate.

If there is good control of the load power factor, the cable current is proportional to the power carried by the transmission system and thus the conductor losses vary by roughly the square of the power delivered. In terrestrial superconducting systems, operating the same cable at current levels below its design point results in reduced efficiency because the refrigeration load due to heat leak into the system dominates the refrigeration loss and is independent of transmitted power. In a space power system, heat leak losses may be negligible, and this design criterion may be completely different. The dielectric losses per unit length are directly dependent on the capacitance and the dissipation factor. In ac superconducting cables, the dissipation factor must be especially low or the low losses of the conductor will be swamped by the dielectric loss. This stringent requirement eliminates many candidate electrical insulation materials for flexible ac cables.

4. AC LOSSES

The current-dependent losses of a superconducting material in alternating fields can be predicted from theory only for well-prepared samples in fields parallel to the surface. In practical conductors the losses can be substantially increased by surface roughness, large grain size, and the addition of materials to the superconductor. In addition, eddy current losses may occur in normal metals laminated to the superconductor.

4.1. INTRINSIC CONDUCTOR LOSSES

Type-II superconductors transporting ac current are subject to hysteretic loss, due to irreversible magnetization during a cycle. For power frequencies (< 20 kHz), this loss is independent of frequency f. The power loss per unit area Q for a slab of superconductor is

$$Q = K\, f\, H_o^3/J_c\,, \tag{1}$$

where H_o is the maximum magnetic field at the surface of the superconductor, and J_c is the critical current density. K is a constant that depends on geometry, and if the superconductor is a slab, then

$$K = 2\mu_o/3\,, \tag{2}$$

where $\mu_o = 4\pi x 10^{-7}$ N/A^2 is the magnetic permeability of free space. At any given temperature T, J_c decreases with increasing H_o.

The losses in the BNL system, which used Nb_3Sn tape, varied as the square of the current, suggesting that hysteresis was not the dominant loss (Forsyth and Thomas, 1986). However, a satisfactory explanation of where this loss actually came from has not yet been verified.

Normal conductors are usually cofabricated with superconductors for stabilization. In some designs, the superconductor shells shield the normal conductor until superconductivity is lost. For any normal conductor in the system, which we assume to be a flat slab, loss is dependent on the skin depth, defined by

$$\delta = (2\rho/\mu_0\omega)^{1/2} , \qquad (3)$$

where ρ is the electrical resistivity, and ω is the angular frequency. The power loss per unit area depends on the surface resistance R_s and the peak surface magnetic field according to

$$Q = R_s H_0^2 , \qquad (4)$$

R_s depends on the thickness t_n of the conductor slab. In the limits of thick and thin conductors

$$R_s = \rho/\delta \qquad (t_n > \delta) \qquad (5a)$$

$$R_s = (2/3)(t_n/\delta)3\rho/\delta \qquad (t_n << \delta) \qquad (5b)$$

4.2. HTS MATERIALS

So far, there have been few analytical or experimental studies of ac losses in HTS materials (Ciszek et al, 1988; Kwasnitza et al, 1988; Clem et al., 1989; Kozlowski and Chen, 1989; Xu et al, 1989)

In practice, it has been found that for tapes of Nb_3Sn, the losses can be greatly reduced from that given in Eq. (1) due to the presence of a surface barrier (Bussiere, 1977). To date, there have been no indications of a similar surface barrier in HTS materials, although future development may lead to its presence.

4.3. SCALING LAWS

In a space power transmission system, it is imperative to design for low loss in order to minimize the weight penalty of the refrigeration system required to remove this heat. If loss minimization is the primary design constraint, then scaling laws for the transmission system are very different from terrestrial systems.

For a superconducting slab, the surface magnetic field is

$$H_0 = J_c t_s \, . \tag{6}$$

where t_s is the thickness of the superconductor. Eq. (6) combines with Eqs. (1) and (2) to give

$$Q = (2/3)\mu_0 f t_s^3 J_c^2 \, . \tag{7}$$

The power transmitted is given by

$$P = VI = VJ_c W t_s \, , \tag{8}$$

where W is the width of the slab. If L is the length of the transmission line, then the fractional loss F in a two-conductor single-phase system is

$$F = 2QLW/P$$

$$F = (4/3)\mu_0 f t_s^2 J_c L/V \, . \tag{9}$$

Clearly, losses are diminished for thin conductors (small t_s, large W). Because the weight of the "bare" transmission line, i.e., without dielectric or mechanical support, is proportional to $t_s J_c W$, the loss per weight of superconductor is proportional to t_s/W, independent of J_c.

5. COOLING

For many space applications, 77 K is approximately "room temperature", i.e., an object may obtain this temperature in radiative equilibrium with its surroundings. The use of passive directional radiant cooling has been used for some time (Annable, 1970) to direct emission from a cooled volume on a satellite to cold regions of space. Further, the theory to optimally design such radiators is well developed (Welford and Winston, 1978).

and from Eq. (6) with $B_o = \mu_o H_o$,

$$B_o = 90 \text{ G}.$$

In the above example, the critical current density J_c for the thickness t_s and maximum field B_o, can be achieved with present technology, although engineering development will be needed to achieve appropriate mechanical integrity, reliability, longevity, etc. Thus, if we form a strip line and let each half of the line radiate away its ac losses, we find that such a superconducting transmission line would not need an external refrigeration system.

For reference, we assume a 0.1 m wide conductor pair at V = 28 V with $J_c = 10^7$ A/m^2 and $t_s = 0.72$ mm. From Eq. (8), the power transmitted is P = 20 kW. From Eq. (9), the loss per meter length per Hertz frequency is Q = 2 mW/m.Hz. As the heat generated by this loss is radiated away, the refrigeration factor is zero. However, the size of the power system must be increased to accommodate the loss.

6. STABILIZATION

The conductor should be cryostatically stabilized at rated current so that, if for some reason (e.g., fault current) the conductor temperature rises and superconductivity is momentarily lost, the conductor will cool rapidly and revert to its superconducting state even if the rated current is not switched off.

The amount of stabilizer can be reduced by having a large difference between the running and transition temperatures. The capital cost of refrigeration may be reduced by running the superconductor at higher temperatures.

With a dc superconducting design, there is no skin depth problem so that full advantage may be taken of high conductivity normal metals to overcome difficulties associated with fault currents and conductor temperature stability. There is no dielectric loss. Fewer conductors are needed, reducing complexity and easing assembly problems (Carter 1973).

7. SYSTEM WEIGHT

For an HTS transmission line to show advantage, it must reduce the overall system weight. A schematic of the major components of a space power system is shown in Fig. 2. The efficiency and weight of each component will vary from mission to mission, but for purposes of general comparison, we will assume typical values.

The generator has a weight of 2 kg/kW, typical of advanced solar cells. Each converter has a weight of 2 kg/kW and and efficiency of 0.95. The cone radiator has a weight of 0.35 kg per watt of heat radiated.

For the HTS conductor in the transmission line, the density is 6300 kg/m^3, with an equal volume stabilizer and support structure of 2700 kg.m^3. For a normal conductor, the density is 2700 kg/m^3, with an equal volume support structure of the same density. The normal conductor has a resistivity of 3×10^{-8} Ωm, approximately equal to aluminum at 300 K. The HTS line suffers a 0.01 loss per km of conductor. The cross-sectional area of the line is uniform and for a particular current density J_c is determined by P_1.

In Figs. 3 and 4 we show the system weight per kW of power at P_{out} by component for a 2-conductor dc system with a line length of 100 m and 1 km, respectively. We have assumed that a refrigeration system is not needed for the HTS line. As evident from the figures, the HTS line has the lower system weight, even for critical current densities as low as 1000 A/cm^2. The aluminum conductor appears to have a minimum system weight at a current density of about 500 A/cm^2. At high current density, the losses require a larger generating and converting capacity. At low current density, the cross-sectional area of the line increases. At 500 A/cm^2, the efficiency e_2 is 0.77 and 0.25, respectively, for 100 m and 1 km. For the latter, the voltage drop along the line is significant.

For an ac system, the results would be similar. The efficiency of the HTS line would still be high. The aluminum conductor would have thin filaments or strips, so in its optimized design at a given frequency, the losses would be similar to the dc case. A major change would be that the converter near the load may not be necessary.

Another concept for the design of the transmission line is to use a directional radiator to reduce the temperature of the aluminum conductor to about 80 K and thus reduce its resistivity by about an order of magnitude. In this case the losses are still significantly higher than for HTS, and the weight of the radiator dominates the system, making the total weight about twice that of the 300 K operation. The weigh of the radiator would need to be reduced by at least an order of magnitude from the assumed value for this concept to be practical.

In the analysis of this section, we have assumed that a refrigerator would not be required for the HTS line. If the line cannot be stabilized without a refrigerator, then the advantage of HTS over a normal conductor is less clear.

8. CONCLUSIONS

Analysis indicates that HTS transmission lines have the potential to reduce the total weight of space power systems. Even with relatively low current densities of 1000 A/cm^2, available with present day materials, HTS has a clear advantage over normal conductors for lines longer than 100 m. Central to this advantage is the assumption that directional radiators can be used to cool the HTS lines in a manner that stably maintains superconductivity. Preliminary analysis indicates that for frequencies below 20 kHz, losses for HTS materials can be made small enough by the use of thin strip geometries that this stability may be possible.

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FIGURE CAPTIONS

Fig. 1. Weight per unit power transmitted per unit length of the conducting part of a two-conductor transmission line as a function of current density for several voltages, assuming a conductor density of 8000 kg/m^3.

Fig. 2. Schematic of major components in space power system.

Fig. 3. System weight for 2-conductor dc system with 100-m-long transmission line using, respectively, HTS conductors with current densities of 1000 and 5000 A/cm^2 and aluminum conductors at 300 K with current densities of 1000, 500, and 250 A/cm^2.

Fig. 4. System weight for 2-conductor dc system with 1-km-long transmission line using, respectively, HTS conductors with current densities of 1000 and 5000 A/cm^2 and aluminum conductors at 300 K with current densities of 1000, 500, 400, and 250 A/cm^2.

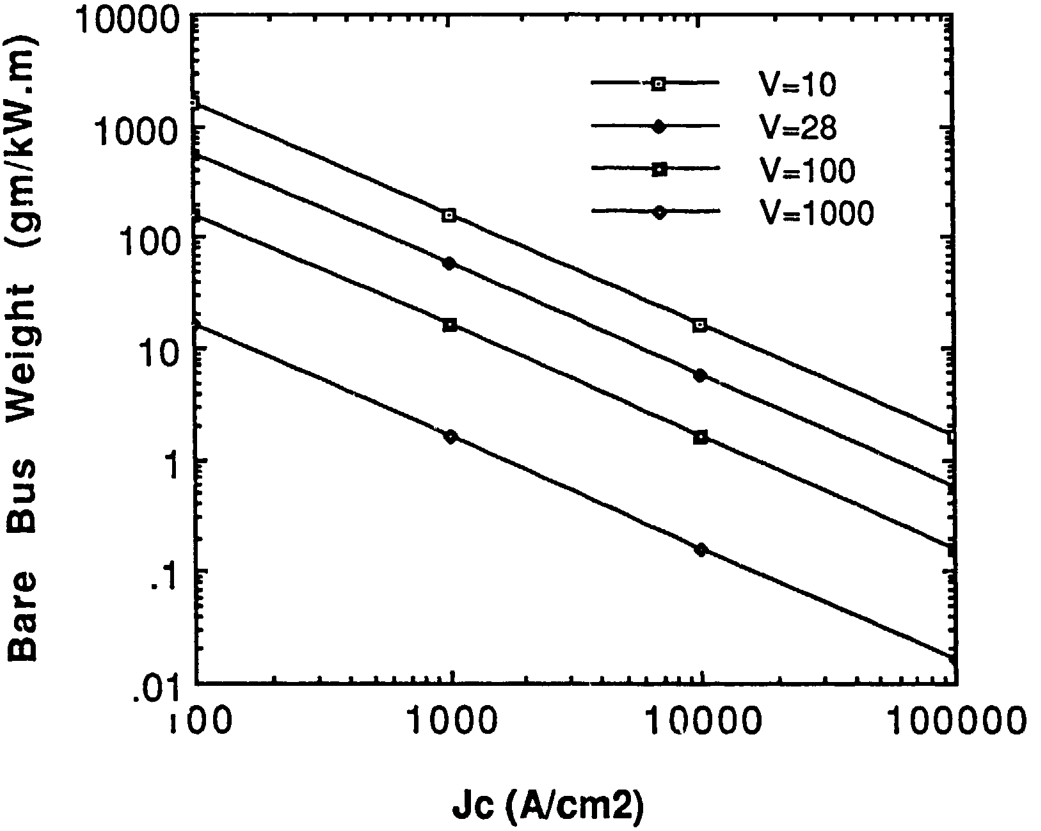
10000
1000
100
10
1
.1
.01
100
1000
10000
100000
Bare Bus Weight (gm/kW.m)
Jc (A/cm2)
V=10
V=28
V=100
V=1000

Fig. 1

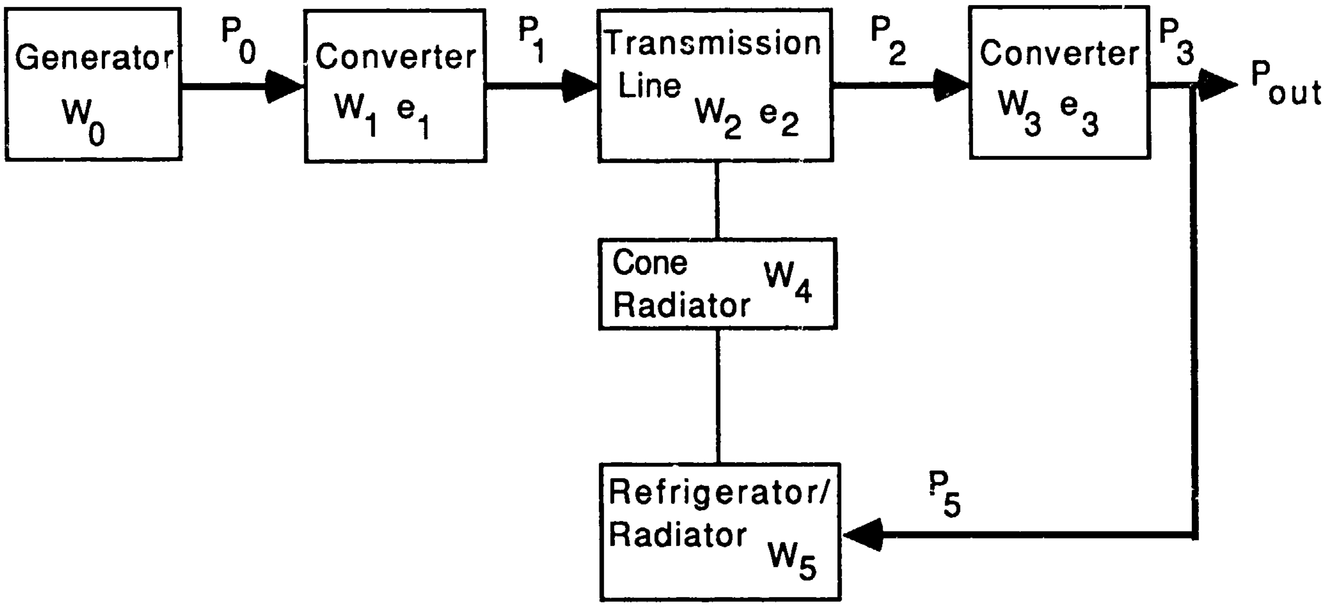
Generator
W0
P0
Converter
W1 e1
P1
Transmission Line
W2 e2
P2
Converter
W3 e3
P3
Pout
Cone Radiator
W4
Refrigerator/ Radiator
W5
P5

Fig. 2

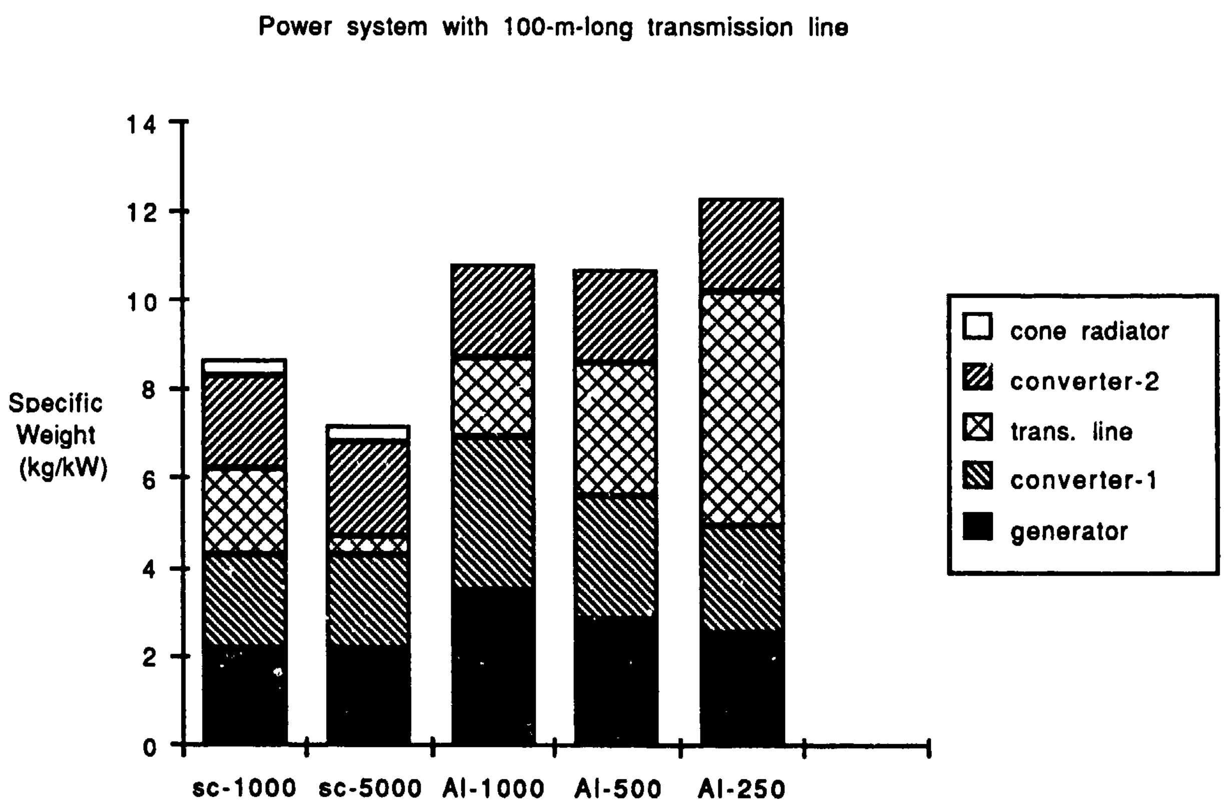
Power system with 100-m-long transmission line
Specific
Weight
(kg/kW)
0
2
4
6
8
10
12
14
sc-1000
sc-5000
Al-1000
Al-500
Al-250
cone radiator
converter-2
trans. line
converter-1
generator

Fig. 3

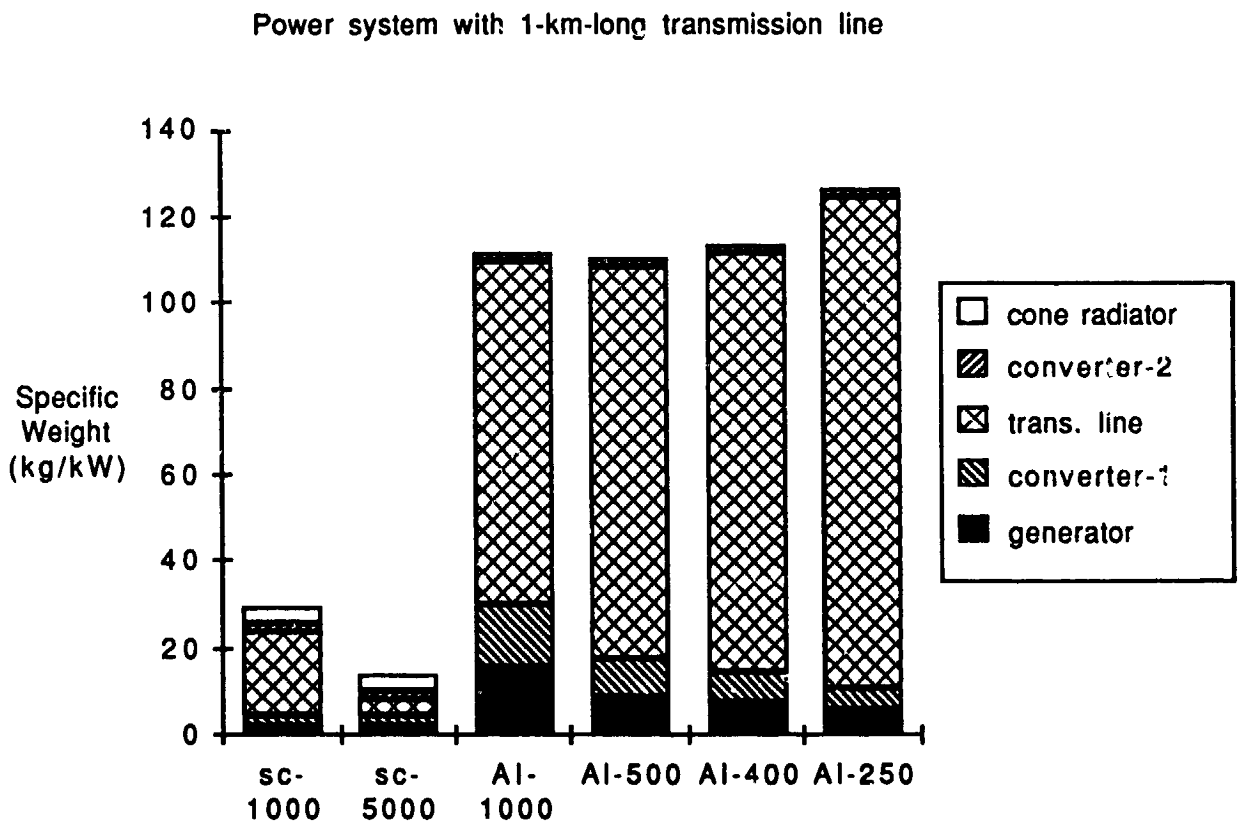
Power system with 1-km-long transmission line
Specific Weight (kg/kW)
140
120
100
80
60
40
20
0
sc-1000
sc-5000
Al-1000
Al-500
Al-400
Al-250
cone radiator
converter-2
trans. line
converter-1
generator

Fig. 4